DE GRUYTER Chem. Prod. Process Model. 2023; ■■■(■■■): 1–19

Jordan O'Callaghan, John Fitzpatrick*, Fergal Lalor and Edmond Byrne

Investigating the energy, environmental, and economic challenges and opportunities associated with steam sterilisation autoclaves

https://doi.org/10.1515/cppm-2022-0053
Received October 20, 2022; accepted March 22, 2023; published online ■■■

Abstract: Despite steam sterilisation in autoclaves being a common industrial method of sterilisation, very little research has been conducted into quantifying the resources these processes demand and their associated environmental impacts. This paper aims to investigate industrial steam sterilisation in autoclaves with particular application to the biopharmaceutical industry. A mathematical model of a steam autoclave was developed to examine relationships between load size, load material properties and autoclave capacity with energy consumption, environmental impact and cost of sterilisation. The two main energy requirements are thermal energy to produce the clean steam for sterilising, and electrical energy for the vacuum pump. The study showed that thermal energy is dominant, particularly as load increases. The percentage of the maximum load at which the autoclave is operated has a major impact on the specific energy requirement or the energy required to sterilise per unit mass of load. For a given autoclave, the energy requirement increases with increased load but the specific energy requirement decreases. This in turn impacts on the emissions and the energy cost. It is thus shown that it is much more energy efficient to operate at higher loads, making the autoclave much more energy and cost effective, and with less environmental impact. There is potential for applying the analysis presented in this work for conducting optimisation studies for determining the sizes of autoclaves that could minimise the energy requirement, environmental impact and economic cost (3E) of investments for specified load versus time profiles.

Keywords: 3E; biopharmaceutical; economic; energy; environmental; steam sterilisation.

Nomenclature

C_{pl}	specific heat of load (kJ kg^{-1} °C^{-1})
C_{pw}	specific heat of water (kJ kg^{-1} °C^{-1})
C_{pss}	specific heat of stainless steel (kJ kg^{-1} °C^{-1})
H_{load}	heat energy required to heat the load to the sterilisation temperature (kJ)
H_{loss}	heat loss from autoclave to the surroundings (kJ)
$\dot{H}_{\text{loss}}$	rate of heat loss from autoclave to surroundings (kJ s^{-1})
H_{struct}	heat energy required to heat the autoclave chamber structure (kJ)
$Q_{\text{autoclave}}$	autoclave steam energy requirement (kJ)
Q_{boiler}	heat energy requirement to produce clean steam in clean steam boiler (kJ)
$Q_{\text{boiler\_losses}}$	heat energy requirement to compensate for boiler losses in clean steam boiler (kJ)
Q_{chamb}	steam energy requirement for uncondensed steam in the autoclave chamber (kJ)
Q_{cond}	steam energy requirement for conditioning (kJ)
Q_{load}	steam energy requirement to heat load to sterilisation temperature (kJ)

***Corresponding author: John Fitzpatrick**, Process & Chemical Engineering, School of Engineering, University College Cork, Cork, Ireland, E-mail: j.fitzpatrick@ucc.ie. https://orcid.org/0000-0003-4687-3977
Jordan O'Callaghan, Fergal Lalor and Edmond Byrne, Process & Chemical Engineering, School of Engineering, University College Cork, Cork, Ireland

Q_{loss}	steam energy requirement to compensate for heat loss to surroundings (kJ)
Q_{struct}	steam energy requirement to heat autoclave chamber structure (kJ)
Q_{WFI}	thermal energy requirement to produce WFI (kJ)
m_l	mass of load (kg)
m_{struct}	mass of autoclave chamber structure (kg)
M_S	mass of steam to autoclave (kg)
M_{S_cond}	mass of steam for conditioning (kg)
M_{S_load}	mass of steam to heat the load (kg)
M_{S_chamb}	mass of steam to fill the chamber (kg)
M_{S_struct}	mass of steam for to heat the autoclave structure (kg)
M_{S_loss}	mass of steam to compensate for heat loss (kg)
N	impeller speed (rpm)
p	pressure (Pa)
p_0	initial pressure (Pa)
P	pump power requirement (kW)
R_{conv}	convective heat transfer resistance from autoclave to surroundings (°C kW^{-1})
R_{wall}	conductive heat transfer resistance through autoclave door wall (°C kW^{-1})
S	pump gas suction volumetric flowrate (m^3 h^{-1})
t	time (s)
t_S	sterilisation cycle time (s)
T_i	initial temperature of WFI (°C)
$T_{initial}$	initial temperature of load (°C)
T_S	temperature of boiling steam at the corresponding operating pressure (°C)
T_{surr}	temperature of autoclave surroundings (°C)
V	autoclave internal volume (m^3)
V_{chamb}	autoclave internal volume accessible to steam (m^3)
$V_{enclosed}$	empty volume within a load that steam cannot penetrate into (m^3)
V_{load}	volume of load material (m^3)
$V_{max\ load}$	maximum load volume in autoclave (m^3)
$\%V_{max\ load}$	maximum load volume expressed as a percentage of autoclave internal volume (%)
v_{steam}	steam specific volume (m^3 kg^{-1})
WFI	water for injection
η_b	clean steam boiler efficiency
λ_v	latent heat of vaporisation of water (kJ kg^{-1})

1 Introduction

Global warming is likely to reach 1.5 °C above pre-industrial levels between 2030 and 2052 if it continues to increase at the current rate, which would result in higher mean temperatures, higher instances of extreme weather, drought, and rising sea levels [1]. Carbon emissions are responsible for almost two-thirds of global greenhouse gas emissions [2], while industrial processes are responsible for approximately 22 % of carbon emissions. Therefore, in order to limit the impact of climate change, more sustainable methods of industrial processes, including biopharmaceutical processes are required [3]. This extends to the sustainable use of phase change materials, such as steam in such industrial processes [4, 5], as steam systems account for roughly 30 % of the energy used in manufacturing facilities [6]. According to Hasanbeigi et al. [7], opportunities for improving inefficiencies in steam systems are plentiful. Hasanbeigi et al. also found that the total cost of saving a unit of energy is lower than purchasing a unit of energy. Therefore there is also an economic incentive for industries to improve energy efficiency in their steam systems. Mousavi et al. [8] also highlighted the importance of considering both energy and water consumption. The analysis under respective energy, environmental, and economic imperatives could be classified as 3E, or sometimes 4E (referring to energy, exergy, economic and environmental considerations) [9], or even 6E (incorporating exergoeconomic, exergoenvironmental) [10], an approach which has been applied to various industrial sectors such as optimized novel power generation and geothermal and solar-based multigeneration systems [11–13]. The outputs of these analyses typically involve the estimation of costs per unit energy and/or per unit mass.

Sterilisation procedures are used to eliminate pathogens and biological agents from a surface in order to remove the adverse risks related to their presence, notably in the food and medical industries [14]. A common method is 'moist-heat' or steam sterilisation. This method utilises saturated steam at temperatures of 121 °C for a specified period of time to denature biological substances and destroy micro-organisms [14]. Steam is by far the most common sterilant used in industry but other sterilants are available. Steam sterilisation uses no toxic chemicals, which gives it an advantage over chemical sterilants. Steam possesses great microbicidal and sporicidal properties and acts rapidly. However, steam sterilisation has a high overall environmental impact when compared to other forms of sterilisation [15]. Consequently, it is especially important that methods of improving energy efficiencies during steam sterilisation processes are found so this environmental impact can be reduced.

The length of time exposed to a sterilant is a critical factor because all the organisms to be removed do not die at the same time. A common time and temperature combination is 121 °C for 12 min [14]. Saturated steam must come into contact with respective surfaces to be sterilised so that energy can be transferred. Therefore, nothing must come between the steam and the surface to be sterilised. This is a challenge because most of the equipment that needs to be sterilised, such as vials and tubing contain a lot of air which can act as an insulating barrier. Air will inhibit heat transfer, thus compromising the sterilisation process. Therefore, it must be removed from the chamber before direct steam contact can occur [16]. This is accomplished by the use of a series of vacuum pulses that pull a vacuum and remove air from the chamber prior to sterilisation.

Items must be dry before they can be aseptically removed from the steriliser. Condensation occurs as a result of steam contact with the cooler surfaces of the load. The presence of condensation can cause re-contamination of the load as microbes will thrive in warm, damp conditions [16]. A steam steriliser dries the load after sterilisation by drawing a deep vacuum in the chamber. A vacuum of 6.9 kPa is recommended for efficient drying. At these pressures, water boils at much lower temperatures and can be removed as steam through the steriliser's vacuum system.

Two common methods of steam sterilisation used in industry are 'steam-in-place' (SIP) and steam sterilisation autoclaves. Steam-in-place is a method for timed in-line sterilisation of the upstream and downstream biopharmaceutical production train using "clean steam", whereas an autoclave is a pressure chamber that subjects its contents to pressurised saturated steam [17]. The "clean steam" used must be made from very pure water and is defined by the purity of the water that is used to make it. Two grades of high purity water that are defined in the US *Pharmacopeia* are purified water and water for injection (WFI) [18, 19]. Purified water must meet specifications for conductivity, total organic carbon, and a microbial specification. WFI is of a higher purity than purified water. It must meet the same chemical specification but has a much higher microbial specification.

The motivation for the study presented in this paper originated from one of the authors who worked in the biopharmaceutical industry. Autoclaves are used in the biopharmaceutical industry to sterilise laboratory instruments and components, and production equipment such as agitators, bioreactor components, and tubing. This requires steam energy and water, which has consequential environmental impact and cost. For a given autoclave, the load to be sterilised may vary considerably over time in terms of mass or volume of load, the type of load and the material properties of the load, including composition and thermal properties. Consequently, this acted as the motivation to investigate these various factors and how they influence steam and water energy requirements, with a view to lowering environmental impact and cost of autoclaving.

An initial review of the literature showed that there was much work presented associated with autoclaving in the canning industry, in particular the steam sterilisation of food and feedstuffs, where autoclaves are typically loaded to capacity with canned material. However, there was little of relevance to autoclaving of components in the biopharmaceutical industry. One such relevant study to assess the impact of autoclave use over a long period of time is that conducted by McGain et al. [20] at the Sunshine Hospital in Melbourne, Australia. The purpose of the aforementioned study was to quantify, for the first time, steam steriliser resource consumption to provide baseline environmental data and identify possible efficiency gains. This research was carried out on hospital steam sterilisers to sterilise various hospital items, such as surgical instruments. McGain et al. [20] sought to find the amount of steriliser electricity (used to run the steam generator, the vacuum pump and the autoclave controller) and water used for active cycles (used to sterilise loads) and for autoclave standby, as well as the relationship between water and electricity consumption and the mass and type of items sterilised. The results showed that 60 % of the total electricity usage was used for active sterilisation cycles, while the remaining 40 % was used during standby time and test cycles. In relation to water usage, 79 % of the total was used for active sterilisation cycles. The total electricity and water consumption per mass sterilised was estimated to be 1.9 kWh kg^{-1} and 58 L kg^{-1}, respectively. McGain et al. [20] concluded that considerable electricity and water use occurred during autoclave standby. Load mass to be sterilised was only moderately predictive of electricity consumption and light loads were common yet inefficient. This work quantified, for the first time, long-term electricity and water use of hospital steam autoclaves, and in doing so provided useful input data for future life cycle assessments of reusable, steam-sterilised equipment and components. Further, it also identified opportunities for improved autoclave efficiencies, including shutting down of idle autoclaves and reducing the number of light autoclave loads.

In this paper, a mathematical model is presented that is used to quantify the energy and water requirements as well as the environmental emissions and economic operating cost of a steam sterilisation process in an autoclave. The model is used to provide a more in-depth fundamental study in terms of evaluating the constituent causes of the total energy and water requirements, and to investigate the effect of parameters, including autoclave capacity, load volume and mass, and load material properties. The modelling is then used to highlight approaches to lowering environmental impact and operating cost associated with steam autoclaves.

2 Mathematical model

2.1 Autoclave cycle

To understand the energy and mass inputs and outputs of the sterilisation process in an autoclave, a process in accordance with ISO 17665 is chosen and consists of the following five major phases [21]:

(i) Air is removed from the steriliser chamber containing the load by a combination of vacuum and steam pulses. This is referred to as conditioning.
(ii) Saturated steam enters the steriliser chamber until the desired temperature and pressure are reached.
(iii) This temperature and pressure are maintained by saturated steam for the required time.
(iv) Steam is then exhausted from the steriliser chamber, causing a vacuum.
(v) Finally, air is admitted to the steriliser chamber through a microbiologically-retentive filter until atmospheric pressure is reached.

According to this operation, the principal inputs for a steam sterilisation autoclave are water for steam production, a source of heat to convert water to steam, electricity to power the vacuum pump, and water to run the vacuum pump.

A sterilisation process calculated to provide a minimum 12-log reduction of microorganisms having a D-value of 1 min at 121 °C is used. This is the case for *Geobacillus stearothermophilus* [22]. Validation of a sterilisation process based on this value is associated with an overkill cycle of 121 °C maintained for a minimum period of 15 min [16]. As a safety factor and to ensure sterilisation has taken place, a period of 25 min is chosen for the sterilisation process.

The autoclave is treated as a box, as illustrated in Figure 1, and is initially full of air. For the purpose of the calculations, autoclaves with internal volumes of 1 m^3 and 4 m^3 are considered. Air is removed using a vacuum pump in the conditioning phase. Saturated steam then enters with a temperature of 121 °C and 2 bar pressure, and is maintained for 25 min to sterilise the load. The steam exits, leaving a vacuum and the vacuum is maintained to dry the load. Air is then allowed back in until atmospheric pressure is reached. Figure 2 illustrates the pressure values attained throughout the autoclave cycle, and is based on work presented by Dion and Parker [16]. Heat required to heat the autoclave structure during the sterilisation process and heat losses to the environment from the autoclave are also considered. The equations used in the mathematical model are presented in the sections below, and the calculations were executed using Microsoft Excel. Like any modelling study, the results do depend on the assumptions made and parameter values used.

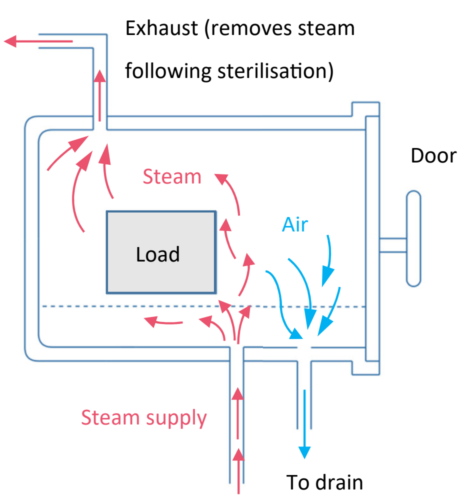

Figure 1: Side-on view of a typical steam sterilisation autoclave.

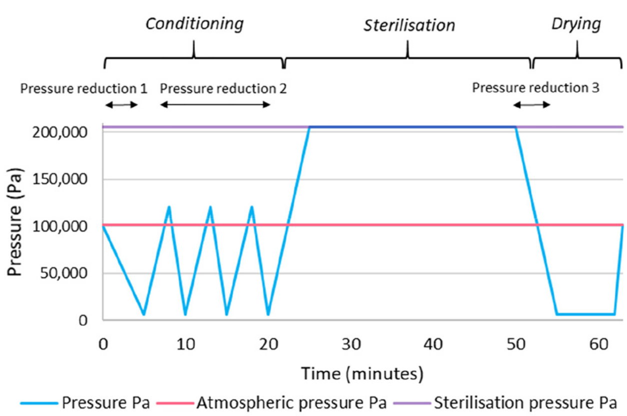

Figure 2: Typical chamber pressure profile during a sterilisation cycle at 121 °C.

2.2 Load volume and mass

The load refers mainly to material associated with the components to be sterilised. However, autoclaves often contain trays to support loads in the autoclave, thus for the sake of simplicity, mass of the load and mass of the load trays are combined and referred to as mass of load.

The maximum mass of load that can be sterilised in an autoclave of a given volume is a very important parameter in this study. An autoclave cannot be totally filled without impacting the effectiveness of the autoclave [23]. It is important to leave sufficient room for steam circulation. It is also vital that there is enough space between the items to be sterilised to allow for adequate steam penetration throughout the load. Furthermore, most components to be sterilised are not solid blocks of material. They have hollow constructions, such as sections of pipework, or have irregular shapes that are spaced out from each other, such as surgical instruments. All this leads to the majority of the chamber volume not being occupied by load material but being occupied by free space even at maximum load. Considering this, the percentage maximum volume occupied by the load material ($\%V_{\text{max load}}$), such as stainless steel in a pipe section, is defined in Equation (1).

$$\%V_{\text{max load}} = \frac{V_{\text{max load}}}{V} \tag{1}$$

where $V_{\text{max load}}$ is the maximum volume of the load material in an autoclave chamber having an internal volume V. In this study, two values of $\%V_{\text{max load}}$ are used to investigate its effect, i.e. 4 % and 20 %. With this, the maximum load value is determined for a given sized autoclave using Equation (1). The corresponding maximum load mass is determined by multiplying this volume times the density of the load material. Stainless steel is chosen as a load material, as most surgical instruments and manufacturing equipment are constructed from stainless steel.

Some loads may have hollow construction that is closed so that no steam can penetrate the object (e.g. a closed container). This results in an enclosed volume ($V_{enclosed}$) that steam cannot penetrate into. Considering the above, the volume of the autoclave chamber available to steam (V_{chamb}) is give in Equation (2).

$$V_{chamb} = V - V_{load} - V_{enclosed} \tag{2}$$

where V_{load} is the volume of the load material. In this study, $V_{enclosed}$ is mainly assumed to be zero, but some analysis is presented to show how it can influence the results.

2.3 Vacuum pump electric energy and service water requirement

A liquid ring pump is chosen for the autoclave operation considered in this paper. The main advantages that liquid-ring pumps have over diaphragm pumps are the high flowrates that they can obtain as well as the substantial vacuum they can pull (~97 %) [24].

As mentioned earlier, Figure 2 illustrates the pressure values attained throughout the autoclave cycle [16]. A vacuum is initially pulled from atmospheric pressure down to 0.06 bar to remove most of the air. This is followed by 3 steam pulses to remove any residual air, where a vacuum is pulled to reduce the pressure from 1.2 bar to 0.06 bar for each of these pulses. After sterilisation, a final vacuum is pulled from 2 bar to 0.06 bar to dry the load. Figure 2 also provides an insight into the suction times for each of the five suctions, which are around 5 min for the initial suction, 2 min each for the next three suctions and 5 min for the final drying suction after load sterilisation. These values are applied in Equation (3) to obtain the suction volumetric flowrate (S) for each of the suctions to decrease the pressure in a sealed container from an initial value p_0 to some value p using a vacuum pump [25].

$$S = \frac{V}{t}\ln\left(\frac{p_0}{p}\right) \tag{3}$$

where V is the internal volume of the container, such as the autoclave, and t is the suction time available. The largest suction volumetric flowrate is obtained for the 2-min suctions, which is around 90 $m^3\,h^{-1}$ and 360 $m^3\,h^{-1}$ for autoclaves with 1 m^3 and 4 m^3 internal volumes, respectively. This is used to select a suitable vacuum pump that could supply these suction flowrates for the respective autoclaves. For the purpose of the model, a Sterling SIHI LEMD series 162 liquid ring vacuum pump is selected for the 1 m^3 autoclave and a Sterling SIHI LEMD series 427 liquid ring vacuum pump is selected for the 4 m^3 autoclave. Values of the electrical power requirement and service water requirement for each of the pumps is obtained from manufacturer brochures [24]. These values are then used to evaluate pump energy and water requirements over their 16-min operation time during an autoclave cycle.

2.4 Autoclave steam and steam energy requirement

During the operation of an autoclave cycle, steam energy is required for the following:
- Conditioning (Q_{cond})
- Load heating (Q_{load})
- Steam to fill chamber (Q_{chamb})
- Autoclave chamber structure heating (Q_{struct})
- Heat losses from autoclave to surrounding environment (Q_{loss})

Thus, the heat input into the WFI to produce clean steam for the autoclave ($Q_{autoclave}$) is given in Equation (4).

$$Q_{autoclave} = Q_{cond} + Q_{load} + Q_{chamb} + Q_{struct} + Q_{loss} \tag{4}$$

The corresponding masses of steam required to supply this energy is given in Equation (5).

$$M_S = M_{S\_\text{cond}} + M_{S\_\text{load}} + M_{S\_\text{chamb}} + M_{S\_\text{struct}} + M_{S\_\text{loss}} \quad (5)$$

Evaluation of the constituent steam energy requirements listed above and the corresponding masses of clean steam required are outlined in the following Sections 2.4.1–2.4.5. Clean steam is produced from vaporising WFI in a clean steam boiler. There is energy required to produce the WFI and there are energy losses in the clean steam boiler. These are considered in Section 2.4.6.

2.4.1 Steam and steam energy required for conditioning

Initially, conditioning is undertaken to remove air from the autoclave chamber, which includes three conditioning steam pulses, as illustrated by pressure reduction 2 in Figure 2. During each of these steam pulses the pressure increases from 0.06 bar to 1.2 bar. The mass of steam required for conditioning (M_{S_cond}) is given in Equation (6).

$$M_{S\_\text{cond}} = 3 \times \left(\frac{V_\text{chamb}}{v_\text{steam}}\right) \quad (6)$$

where V is the internal volume of the autoclave, V_load is the volume of load material and v_steam is the specific volume of steam at the operating pressure, which is 1.428 $m^3\ kg^{-1}$ at 1.2 bar pressure.

The associated heat energy input into WFI to produce the clean steam for conditioning (Q_cond) is given in Equation (7).

$$Q_\text{cond} = M_{S\_\text{cond}} \left[C_{pw} (T_S - T_i) + \lambda_v\right] \quad (7)$$

where T_S and λ_v are the boiling temperature of the steam and its corresponding latent heat of vaporisation, respectively, and T_i and C_{pw} are the initial temperature of WFI (20 °C) and its specific heat capacity, respectively.

2.4.2 Steam and steam energy required to heat load

Steam condenses on contacting the load as it heats it to the sterilisation temperature. The heat transferred from the condensing steam (H_load) is estimated in Equation (8).

$$H_\text{load} = m_l C_{pl} (T_S - T_\text{initial}) \quad (8)$$

where m_l is the mass of the load, C_{pl} is the specific heat capacity of the load, and T_initial is the initial temperature of the load (20 °C). The mass of steam required to supply this heat energy (M_{S_load}) is evaluated in Equation (9).

$$M_{S\_\text{load}} = H_\text{load}/\lambda_v \quad (9)$$

where λ_v is latent heat of condensation of the steam, which is 2202 kJ kg^{-1} for 2 bar steam. The associated heat energy input into WFI to produce the clean steam for heating the load (Q_load) is evaluated using an equation similar to Equation (7), where mass of steam is M_{S_load}.

2.4.3 Steam and steam energy required to fill the chamber

The internal volume of the autoclave chamber not occupied by the load (and trays) is occupied by steam. The mass of steam filling the chamber (M_{S_chamb}) is given in Equation (10).

$$M_{S\_\text{chamb}} = \frac{V_\text{chamb}}{v_\text{steam}} \quad (10)$$

At 2 bar pressure, the specific volume of steam is 0.866 $m^3\ kg^{-1}$. The associated steam energy (Q_chamb) is evaluated using an equation similar to Equation (7), where mass of steam is M_{S_chamb}.

2.4.4 Steam and steam energy required to heat autoclave chamber structure

Steam is required to heat autoclave chamber structure from the initial temperature up to the sterilisation temperature. The chamber structure is modelled as a stainless-steel structure with a thickness of 5 mm, which is of sufficient structural thickness for autoclaves operated at 2 bar pressure. The volume of structural stainless steel is evaluated for a cubic chamber of known internal volume, and its corresponding mass (m_{struct}) is estimated using the density of stainless steel. The corresponding heat transferred from the condensing steam to heat this mass (H_{struct}) is estimated in Equation (11).

$$H_{\text{struct}} = m_{\text{struct}} C_{pss} \left(T_S - T_{\text{initial}}\right) \tag{11}$$

where C_{pss} is the specific heat of stainless steel (0.502 kJ kg^{-1} °C^{-1}). The associated heat energy input into WFI to produce the clean steam for heating the chamber structure (Q_{struct}) is evaluated using an equation similar to Equation (7), where mass of steam is M_{S_struct}.

2.4.5 Steam and steam energy required to replace heat loss to the surroundings

Sterilisation is taking place at 121 °C, thus heat loss will occur to the surroundings, however this will be influenced by how well the autoclave chamber is thermally insulated. Heat is transferred by conduction and convection from the external surface area of the autoclave chamber to the surrounding environment. Initial calculations showed that heat loss by radiation was negligible. Considering this, the rate of heat loss ($\dot{H}_{\text{loss}}$) is expressed in Equation (12).

$$\dot{H}_{\text{loss}} = \frac{\left(T_S - T_{\text{surr}}\right)}{R_{\text{wall}} + R_{\text{conv}}} \tag{12}$$

where T_{surr} is the temperature of the surroundings (20 °C), R_{wall} and R_{conv} are the resistances to heat transfer due to conduction through the chamber insulation and convection, respectively. These resistances are estimated from considering the thickness of insulation (0.02 m), the surface area of the chamber (which is calculated based on the geometry of a cube and the internal volume of the chamber), the thermal conductivity of the insulation (0.035 W m^{-1} °C^{-1}), and the convective heat transfer co-efficient (20 W m^{-1} °C^{-1}).

The amount of heat energy loss (H_{loss}) from the autoclave during the sterilisation period of time is given in Equation (13).

$$H_{\text{loss}} = \dot{H}_{\text{loss}} \left(t_S\right) \tag{13}$$

where t_S is the sterilisation time, which lasts 25 min or 1500 s. The mass of steam required to compensate for heat loss (M_{S_loss}) is evaluated using an equation similar to Equation (9). The associated steam energy (Q_{loss}) is evaluated using an equation similar to Equation (7), where mass of steam is M_{S_loss}.

2.4.6 Energy required to produce WFI and boiler energy losses

The clean steam for the autoclave is produced by first producing WFI, which is then vaporised in a clean steam boiler, as illustrated in Figure 3. There is an energy requirement for the production of WFI and there are energy losses associated with the boiler for the clean steam production. These energies are included in the modelling and are considered in this section.

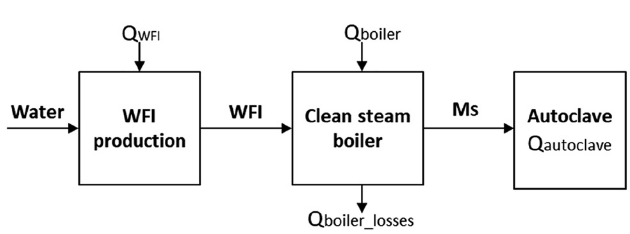

Figure 3: Heat energies involved in the production of a mass of clean steam (M_S) for the autoclave.

A paper investigating the environmental impact of WFI generation by Idris et al. [26] used *SuperPro* to model a process to produce WFI using a multiple effect distillation (MED) system. It was assumed that the MED has 5 effects. The final energy required per kg of WFI produced was estimated to be 857.5 kJ. This value is used to provide an estimate of the thermal energy required to produce the WFI needed (Q_{WFI}) for the clean steam supply to the autoclave, as presented in Equation (14).

$$Q_{\text{WFI}} = 857.5\,(M_S)\,\text{kJ} \tag{14}$$

The energy input into the clean steam boiler (Q_{boiler}) depends on the autoclave steam energy requirement and the boiler efficiency (η_b). This relationship is expressed in Equation (15).

$$Q_{\text{boiler}} = Q_{\text{autoclave}}/\eta_b \tag{15}$$

The boiler efficiency is given a value of 0.85 (or 85 %). The boiler energy losses ($Q_{\text{boiler\_losses}}$) are given in Equation (16).

$$Q_{\text{boiler\_losses}} = Q_{\text{boiler}} - Q_{\text{autoclave}} = Q_{\text{autoclave}}\left(1/\eta_b - 1\right) \tag{16}$$

3 Results and discussion

3.1 Energy requirements

This section initially evaluates the energy requirement of a 1 m^3 autoclave at full load and presents the breakdown of constituents of the total energy requirement. The section then investigates the effects of a number of parameters on the energy requirements, including the mass of load sterilised, autoclave size and the physical properties of the load (specific heat and density).

3.1.1 Evaluation of energy requirement for a 1 m^3 autoclave operated at full load

In this section, energy requirement data is presented in Table 1 for a 1 m^3 autoclave, where the percentage maximum volume occupied by the load material ($\%V_{\text{max load}}$) is 4 % and this maximum is fully loaded to 100 % with stainless steel load, which results in a load mass of 312 kg. From the data presented in Table 1 it is clear that the total thermal energy required for the autoclave cycle is much greater (~18 times) than the electrical energy needed to run the vacuum pump.

Of the total thermal energy requirement, the autoclave represents around 67.7 %, the WFI production is 22.15 % and clean steam boiler losses are around 10.15 %. This remains a constant breakdown irrespective of load because the energy associated with WFI production and clean steam boiler losses is directly related to the thermal energy requirement of the autoclave supplied by the clean steam.

Of the autoclave steam thermal energy (Table 1), less than half or around 44 % is needed to heat the load. In relation to the remainder, 33 % is needed to heat the autoclave chamber structure, 12 % is for conditioning, 7 % for steam filling the chamber and 4 % for heat losses. Of course, the energy requirement and their breakdown will be influenced by the mass of load sterilised, which is discussed in detail in the next section.

The heat loss to the environment is relatively low at 4 % but this does depend on insulation. If the 2 cm thickness insulation is removed, then the autoclave thermal energy requirement increases from 43 to 63 MJ, with heat loss accounting for 35 % of the autoclave thermal energy requirement. Consequently, it is important to ensure that there is adequate insulation to prevent heat loss being a significant contributor to the autoclave steam energy requirement.

Table 1: Energy and water requirements for 1 m^3 autoclave operated at 100 % of maximum load for $\%V_{max\_load}$ = 4 % and 20 %.

Component of autoclave operation	$\%V_{max\_load}$ = 4 %	$\%V_{max\_load}$ = 20 %
Load mass (kg)	312	1560
Electrical energy (MJ)		
Vacuum pump energy	3.46	3.46
Autoclave steam thermal energy (MJ)		
Total autoclave thermal energy	42.9	117.0
Breakdown of energy associated with:		
Conditioning	5.2	4.4
Load heating	18.9	94.3
Filling chamber with steam	2.9	2.4
Structure heating	14.1	14.1
Losses to surroundings	1.7	1.7
Clean steam thermal energy (MJ)		
Thermal energy to produce WFI	14.0	38.2
Clean steam boiler losses	6.4	17.5

3.1.2 Effect of load sterilised on energy requirements

The mass of load sterilised will have a major influence on the energy requirement. The mass of load is influenced by the load capacity of the autoclave (or how much load can be placed in the autoclave) and how much of this capacity is actually used in practice.

In Section 2.2, the percentage maximum volume occupied by the load material ($\%V_{max\_load}$) is defined and is used to evaluate the maximum volume and mass of the load material in a given autoclave. This will vary depending on the type of loads being sterilised, as highlighted in Section 2.2.1. Two values of 4 % and 20 % are investigated in this study and the results are presented in Table 1. At $\%V_{max\_load}$ = 20 %, the load mass is 5 times greater than at $\%V_{max\_load}$ = 4 %, and this consequentially translates into the load heat requirement being also 5 time greater. However, the autoclave steam thermal energy requirement is only around 2.7 times greater. This is because the structure and heat loss terms remain unchanged, and the conditioning and chamber filling energies reduce a little due to higher load volume resulting in lower non-load space volume in the chamber.

As highlighted above, the mass of load in the autoclave is also influenced by how much of the autoclave load capacity is actually utilised in practice. Many autoclaves for various reasons are not operated at 100 % of their maximum load capacity. The model is applied to perform energy calculations for different loads or percentage of maximum load. Calculations are carried out in the range of 0 %–100 % of max load for a 1 m^3 autoclave with a $\%V_{max\_load}$ = 4 %. Figure 4 illustrates the effect of percentage of maximum load on the autoclave thermal energy requirement and the pump energy needed to supply the vacuum. Autoclave thermal energy requirement is much greater than pump electrical energy requirement, as illustrated by the different scales used in Figure 4.

Pump energy does not change with increased load in the model. This is because it is a specific pump operating at a fixed speed. However, as the load volume increases, there is less residual air removal required and pump suction flowrate requirement will decrease. This requirement is not a major decrease because the non-load volume takes up most of the internal volume ranging from 96 to 100 % depending on autoclave load capacity and percentage used.

Autoclave thermal energy increases with load as expected, as more energy is required to sterilise a greater load. However, it should be noted that even with no load, there is a significant thermal energy requirement of about 24.4 MJ. This is nearly 57 % of the 42.9 MJ at 100 % load. Consequently, increasing load does increase thermal energy requirement but the rate of increase is not as large as may intuitively be expected because of the major

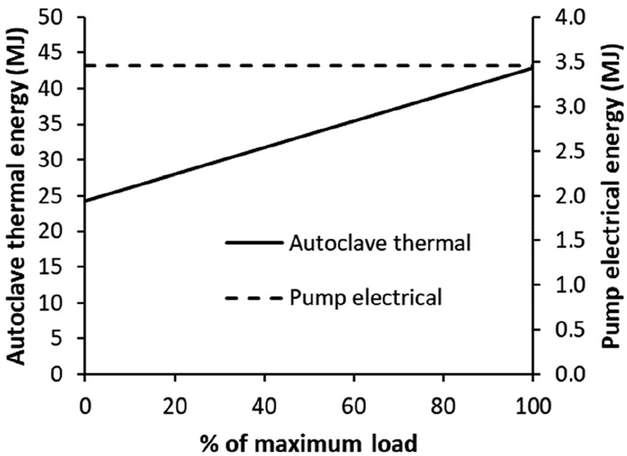

Figure 4: Effect of % of maximum load volume on thermal energy and pump energy requirement.

thermal energy requirement at zero load. McGain et al. [20] also highlight this point, that the load mass was only moderately predictive of energy consumption.

Figure 5 provides a breakdown of the thermal energy and how it is affected by load for a 1 m^3 autoclave with a $\%V_{max\ \_load}$ = 4 %. As expected, load heating requirement increases with higher load, which results in the autoclave steam energy requirement increasing with increased load. WFI thermal energy increases with load because more WFI is required to produce the greater amount of steam needed to sterilise a larger load. Autoclave chamber structure heating is unaffected by load and is the highest contributor to autoclave steam energy requirement up to about 75 % max load. Figure 5 also shows that losses to environment remain constant regardless of percentage of max load sterilised. Steam energy associated with conditioning and chamber fill decreases with higher load, but this is only a small decrease. This is because there is less non-load volume in the chamber at higher loads (i.e. 1 m^3 at 0 % max load and 0.96 m^3 at 100 % max load) resulting in less steam required for conditioning and chamber fill.

As highlighted in Section 2.2, some loads may have an enclosed empty volume ($V_{enclosed}$) that steam cannot penetrate into, such as a closed container. This reduces the volume available for steam in the autoclave, which will correspondingly reduce the steam energies associated with conditioning and chamber fill.

3.1.3 Effect of load sterilised on specific energy requirements

Figure 5 shows that autoclave thermal energy increases with higher loads, however the specific energy (or energy required to sterilise a kg of load) is possibly more important, and this is illustrated in Figure 6. This shows that

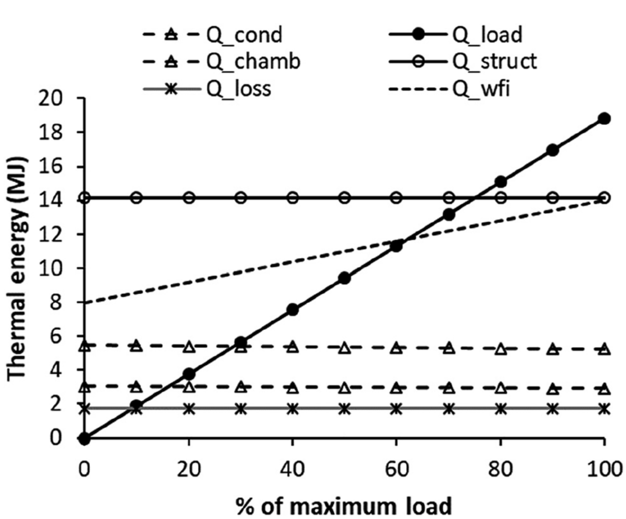

Figure 5: Effect of % of maximum load on the constituents of the clean steam energy.

increasing the load in a given autoclave has a major impact on both thermal and pump specific energy consumed. The sterilisation of a greater load results in lower specific energies, thus it is much more energy efficient to operate an autoclave at higher loads, ideally at its maximum load volume. McGain et al. [20] also highlighted this effect, where it is more energy efficient to operate an autoclave less frequently at higher loads. The rationale for the large reduction in specific energies at higher load are essentially two-fold. Firstly, thermal energy requirement is a significant value with no load and only modestly increases with higher load, as highlighted in the previous section. Secondly, the thermal energy associated with conditioning and chamber filling with steam decreases at higher load, thus the specific energy associated with these constituents is going to decrease even more at higher loads.

From the data presented in Figure 6 it can be established that operating a 1 m^3 autoclave at 100 % of maximum load capacity is around 6 times more steam energy efficient than operating at just 10 % of maximum load capacity. Furthermore, as Figure 6 displays an exponential decrease, then operating at 100 % max load is around 57 times more steam energy efficient than operating at 1 % of max load.

3.1.4 Effect of autoclave size

Two autoclaves, one with a capacity of 1 m^3, and the other having a capacity of 4 m^3 are both loaded at 100 % of their respective maximum load volumes. Table 2 shows the effect of autoclave size on specific energy requirements. The pump specific energies are fairly similar, with the difference being due to the specification of two different pumps.

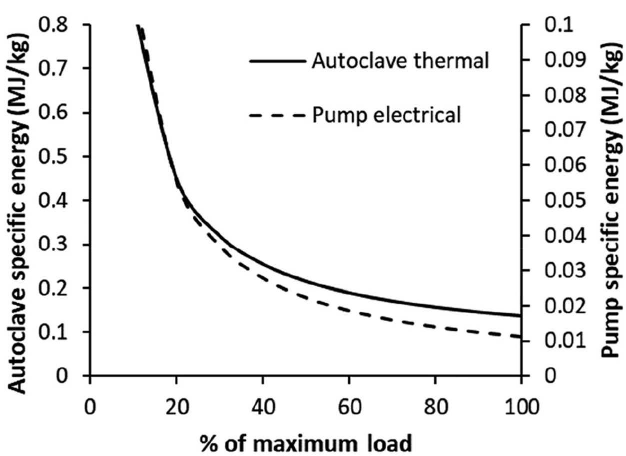

Figure 6: Effect of % of maximum load sterilised on the specific energies for autoclave thermal and pump electrical.

Table 2: Effect of autoclave size on specific energy and specific water requirements, where both autoclaves (1 m^3 volume and 4 m^3 volume) are operating at 100 % of maximum load for $\%V_{max\ load}$ = 4 %.

Component of autoclave operation	1 m^3 autoclave	4 m^3 autoclave
Electrical specific energy (kJ/kg)		
Vacuum pump specific energy	11.1	9.2
Autoclave steam thermal specific energy (kJ/kg)		
Total autoclave thermal specific energy	137.5	106.8
Breakdown of specific energy associated with:		
Conditioning	16.8	16.8
Load heating	60.4	60.4
Filling chamber with steam	9.3	9.3
Structure heating	45.3	18.0
Losses to surroundings	5.6	2.2

Table 2 shows that the autoclave steam specific energy requirement is about 22 % lower for the larger autoclave. However, Table 2 also shows the steam specific energy requirements associated with conditioning, load heating and chamber fill are identical for each autoclave. The reduction at larger autoclave size is associated with the structure heating in particular and heat loss to the environment. The fundamental reason for these differences in specific energy requirements is because load volume has a cubic (or power to the 3) scale-up while structure heating and heat loss are both scaling up with the chamber surface area, which is a square (or power to the 2) scale-up.

3.1.5 Effect of an identical load being processed in two autoclaves of different capacity (1 m^3 and 4 m^3)

A comparison of the energy needed to autoclave a 100 kg stainless steel load in 1 m^3 and 4 m^3 autoclaves is presented in Table 3. The pump energies for the 1 m^3 and 4 m^3 autoclaves are 3.46 and 11.5 MJ, respectively. This shows an expected increase in the electricity needed to power the larger vacuum pump for the larger autoclave, as more residual air needs to be removed from the larger autoclave. The autoclave steam energy consumption for the 4 m^3 autoclave is over double or 115 % greater than if the 100 kg load is sterilised in the 1 m^3 autoclave. The steam energy associated with conditioning and chamber fill shows a 4 times increase and that associated with structure heating and heat loss increases shows a 1.6 times increase.

Considering the above, if an organisation needs to autoclave materials where the majority of the loads are relatively small and there are only a few larger loads, then it may make energy, environmental and financial sense to purchase two autoclaves. One larger autoclave could be reserved for sterilising the infrequent larger loads and an additional smaller autoclave could be purchased to sterilise the numerous smaller loads. This would eliminate inefficiencies caused by running the larger autoclave when the load is not sufficiently large enough to make sufficient use of it.

3.1.6 Effect of specific heat and density of load

The model is now implemented for a fixed volume autoclave (4 m^3) and loaded with stainless steel and polyvinyl chloride (PVC) loads to observe the effect of load material properties on energy requirements, in particular specific heat and density of load. The autoclave is operated with a $\%V_{\text{max \_load}}$ = 4 % and at 100 % of the maximum load, and the results are presented in Table 4. The two loads, while of different masses, have the same volumes. The values for vacuum pump energy are identical, however, the specific pump energy requirement is higher for the PVC because of its lower density [27].

The non-load volume in the chamber is the same irrespective of load material because the load volumes are the same. Consequently, the steam energy requirements for conditioning and chamber fill are the same for both

Table 3: Comparison of requirements for autoclaving an identical load (100 kg stainless steel) in 1 m^3 and 4 m^3 autoclaves.

Component of autoclave operation	1 m^3 autoclave	4 m^3 autoclave
Electrical energy (MJ)		
Vacuum pump energy	3.46	11.5
Autoclave steam thermal energy (MJ)		
Total autoclave thermal energy	30.3	65.1
Breakdown of energy associated with:		
Conditioning	5.4	21.8
Load heating	6.0	6.0
Filling chamber with steam	3.0	12.1
Structure heating	14.1	22.4
Losses to surroundings	1.7	2.8

Table 4: Effect of load specific heat and density on energy and water requirements in a 4 m^3 autoclave operating at 100 % of maximum load (% $V_{max\ load}$ = 4 %).

Energy and water requirements	**Stainless steel**	**PVC**
Density (kg/m^3)	7800	1370
Load mass (kg)	1248	219
Specific heat (kJ/kg °C)	0.502	1
Energy requirement (MJ)		
Vacuum pump energy	11.5	11.5
Autoclave thermal energy	133.3	84.2
Specific energy requirement (kJ/kg)		
Vacuum pump energy	9.2	52.6
Autoclave thermal energy	106.8	384.6
Thermal energy to produce WFI (MJ)		
Thermal energy to produce WFI	43.6	27.6

loads. Also, the structure heat requirement and heat loss are the same irrespective of the load because the chamber volumes are identical. The reason for the difference in autoclave steam energy requirement is due to the load heat requirement which depends on the load material. The stainless steel has a higher load heat requirement of 75.4 MJ in comparison to 26.4 MJ for the PVC. These values are directly related to the density times specific heat for both materials which is 3916 and 1370 kJ m^{-3} $°C^{-1}$ for stainless steel and PVC, respectively. Furthermore, since the specific heat capacity of PVC is twice that of stainless steel [28], it takes twice as much heat to raise the temperature of a unit mass of PVC by 1 °C. Therefore, the autoclave specific thermal energy required is greater for the PVC load. Overall, larger density and higher specific heat capacity results in greater autoclave steam energy requirement, while higher specific heat results in greater autoclave specific steam energy requirement.

3.2 Emissions to the environment

The autoclave emissions that can impact on the natural environment are those associated with the supply of energy to an autoclave, in particular the thermal energy and vacuum pump electrical energy. The autoclave energy to provide the clean steam is usually supplied by utility steam to convert WFI into clean steam and also in the production of the WFI. The utility steam is typically produced in a steam boiler, and consequently the emissions are those associated with the combustion of fuel in the boiler. The vacuum pump requires electrical energy, thus the emissions associated with this depends on the source of electricity and power plant used in its generation. These emissions can be estimated using the calculated thermal and electrical demands of the autoclave in combination with emission factors associated with the combustion of fuel in the boiler and electricity generation.

For example, a 1 m^3 autoclave in which two 50 kg stainless steel loads (~16 % of maximum load) are sterilised separately every day during the year is considered. The thermal energy is supplied using a natural gas boiler with a boiler efficiency of 85 %. The pump electrical energy is supplied from the grid, which has an emissions profile similar to that in Ireland [29]. The annual emissions for the autoclave are presented in Table 5 using emission factors associated with carbon dioxide and NOx emissions [30, 31], natural gas combustion [32, 33], coal combustion [34, 35] and other emission factors [36]. CO_2 accounts for the vast majority of the emissions, and small quantities of carbon monoxide, nitrous oxides, sulphur oxides, particulates, and trace quantities of mercury are also released. As the emissions are associated with energy, the quantity of emissions will be proportional to energy usage. Consequently, the quantity of emissions discharged per kg of load will decrease as the percentage of maximum load volume increases in the autoclave. Therefore, it is more efficient, in terms of emissions reduction, to operate an autoclave at higher loads.

3.3 Water requirements

The water requirements and specific water requirements at different values of percentage of maximum load are presented in Figure 7 for a 4 m^3 autoclave. The major water requirement is for the vacuum pump, as illustrated in Figure 7(a). This greatly exceeds that of the WFI requirement for clean steam at all loads, especially at lower loads. The pump water requirement is 90 % of the total at 100 % max load. As expected, the WFI requirement increases with increased load, as more clean steam is required to sterilise the larger load. The pump water requirement

Table 5: Annual emissions from a 1 m^3 autoclave in which two 50 kg stainless steel loads are sterilised separately every day during the year.

Pollutant	Emissions associated with thermal energy requirement (kg)	Emissions associated with the vacuum pump (kg)	Total emissions (kg)
CO_2	1956	216.25	2172.6
CO	48	4.05	52.5
NO_X	80	8.11	88.4
SO_X	0.35	12.30	12.65
Particulates	0	1.82	1.82
Hg	0	1.78×10^{-5}	1.78×10^{-5}

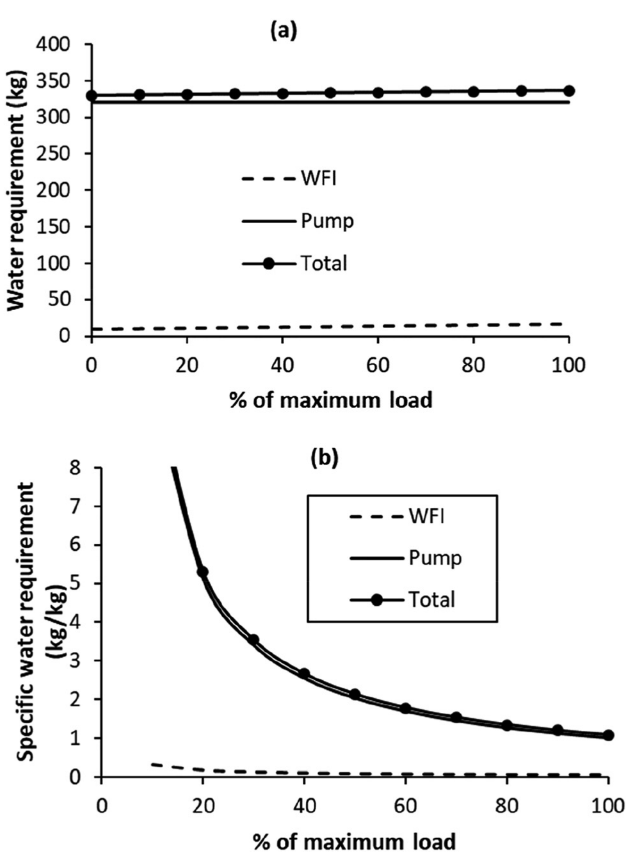

Figure 7: Effect of % of maximum load on (a) water requirement and (b) specific water requirement (kg of water per kg of load) for a 4 m^3 autoclave.

remains the same despite changes in load volume. The pump used for the 4 m^3 autoclave (Sterling SIHI LEMD 427 series liquid ring vacuum pump) requires the same volume of service water regardless of percentage of maximum load volume [24]. Figure 7(b) shows that the specific water requirement greatly decreases with increased load, thus it is desirable from a water resource efficiency perspective to operate at higher loads.

3.4 Cost

The cost associated with an autoclave are its capital cost and operating cost. A major component of the operating cost is the cost of energy. From the previous analysis, autoclave energy cost during a cycle will depend on the size of the load it is autoclaving and will thus vary in a similar way to energy presented in Figure 4. More importantly, the specific energy cost (energy cost per kg of load) will depend on the percentage of maximum load that an autoclave is operating at and will thus behave in a similar manner to specific energy as presented in Figure 6.

To illustrate this, cost calculations were performed on a 4 m^3 autoclave operated at different loads. The cost of grid electricity was taken to be €0.05556/MJ [37], and the cost of supplying clean steam was €0.01861/MJ [37]. Figure 8 illustrates the effect of percentage of maximum load on the energy cost during one cycle and the specific energy cost. Figure 8(a) shows that energy cost increases with greater load, as expected, and that the thermal energy cost is much greater than pump energy cost for all loads. Like with energy, there is a significant energy cost at zero load which is nearly 53 % of the cost at 100 % of maximum load. Figure 8(b) shows the beneficial effect of operating at higher loads by the large reduction in specific energy costs at higher loads. For example, the specific energy cost is nearly 6 times lower when operating at max load in comparison to operating at 10 % of max load.

The above data can be used to calculate the annual cost saving associated with operating at 100 % of max load as opposed to 20 % of max load in a 4 m^3 autoclave. For example, let's say it was required to carry out an autoclave

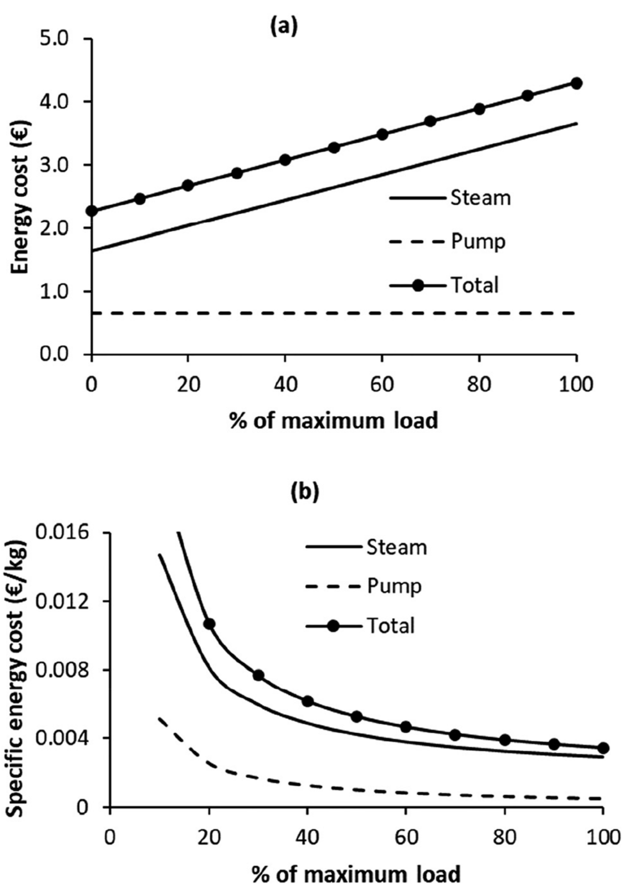

Figure 8: Effect of % of maximum load on (a) energy cost and (b) specific energy cost for a 4 m^3 autoclave.

cycle at 20 % of max load every day for a year. Let's say that this was replaced by an autoclave cycle at 100 % of max load every 5 days throughout the year. After running the model for the two aforementioned scenarios, the sterilisation of 20 % of maximum load every day for a year resulted in a cost of €976. The sterilisation procedure at 100 % of maximum load, every 5 days for a year costs €314. Even though the cost in this example does not represent a large economic value, this is a saving of nearly 68 %. Increasing energy costs would of course increase the cost differential pro-rata, while maintaining the percentage saving.

3.5 Opportunity for energy, emissions, and cost savings

The percentage of maximum load at which an autoclave operates has a major impact on the energy requirement, emissions, and energy costs, as shown in the previous sections. From this, it is desirable to operate consistently at as close to 100 % of maximum load as possible, in order to minimise energy usage, emissions, and energy costs. It may not be possible to do this in practice due to variations in the amount of load requiring autoclaving over time. This can often times lead to the specification of a large autoclave that can deal with the largest load. This will result in inefficiencies if the majority of the loads are much smaller and thus the autoclave is being predominantly operated at a low percentage of maximum load. In this situation, it may be worth having two autoclaves, a small autoclave that is more suitable for routine sized loads and a large autoclave that is occasionally required for the larger loads. This is an interesting optimisation problem to establish the size of the smaller autoclave that can minimise the net present value of the investment in two autoclaves to sterilise a specified load versus time profile. It will depend on whether or not the cost savings can justify the capital expenditure, which will intrinsically depend on how much autoclave activity is required.

4 Conclusions

The two main energy requirements are thermal energy to produce the clean steam for sterilising, and electrical energy for the vacuum pump to remove air prior to sterilisation. Thermal energy is dominant, particularly as load increases. For a given size autoclave, the energy requirement is greater with greater load to be sterilised, as might be expected. However, the energy requirement only modestly increases with increased load. The rationale for this is that there is a significant amount of energy required to operate the autoclave with no load, and the energy requirement only gradually increases as load increases. Of course, more energy is required to heat more load, however some of the constituents of the energy requirement decrease with higher load. These include the steam energy used in initial conditioning to remove air and in filling the chamber during sterilisation, because there is less non-load volume in the autoclave at higher loads.

The study shows that the maximum load capacity of an autoclave and how much of it is utilised in practice has a major impact on the specific energy requirement or the energy required to sterilise a unit mass of load. This in turn impacts on the emissions and the energy cost. It is shown that it is much more energy efficient to operate at higher loads, ideally at 100 % of maximum load. This makes the autoclave much more energy and cost effective, and has less environmental impact. There is potential for applying the analysis presented in this work for conducting optimisation studies for determining the sizes of autoclaves that could minimise the economic cost of investments for specific load versus time profiles.

In the context of a processing plant, the value of the energy, emissions, and cost savings by trying to reduce specific energy requirements do depend on the scale of the autoclaving activity required during production and how this compares to other energy uses. This may prove to be relatively small in some industries, however every initiate to reduce energy and associated emissions and improve cost savings in a processing facility do add up to improve overall performance.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: None declared.
Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

1. Masson-Delmotte V. Global warming of 1.5 °C. Switzerland: Intergovernmental Panel on Climate Change (IPCC); 2018.
2. United States Environmental Protection Agency. Sources of greenhouse gas emissions [Online]; 2017. Available from: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions [Accessed 17 Oct 2022].
3. Lalor F, Fitzpatrick J, Sage C, Byrne E. Sustainability in the biopharmaceutical industry: seeking a holistic perspective. Biotechnol Adv 2019;37:698–707.
4. Seiler D, Donovan D, O'Donnell GE. Industrial steam systems: strategic framework with proxy measurements to evaluate the total cost of steam. J Clean Prod 2019;231:1307–18.
5. Koten H. Phase change materials (PCM) and their applications. In: Recent researches in engineering sciences. Lyon, France: Livre de Lyon; 2021.
6. Yang M, Dixon RK. Investigating in efficient industrial boiler systems in China and Vietnam. Energy Pol 2012;40:432–7.
7. Hasanbeigi A, Harrell G, Schreck B, Monga P. Moving beyond equipment and to systems optimization: techno-economic analysis of energy efficiency potentials in industrial steam systems in China. J Clean Prod 2016;120:53–63.
8. Mousavi S, Kara S, Kornfeld B. A hierarchical framework for concurrent assessment of energy and water efficiency in manufacturing systems. J Clean Prod 2016;133:88–98.
9. Coppitters D, Costa A, Chauvy R, Dubois L, De Paepe W, Thomas D, et al. Energy, exergy, economic and environmental (4E) analysis of integrated direct air capture and CO2 methanation under uncertainty. Fuel 2023;344:127969.
10. Khani N, Manesh MHK, Onishi VC. 6E analyses of a new solar energy-driven polygeneration system integrating CO2 capture, organic Rankine cycle, and humidification-dehumidification desalination. J Clean Prod 2022;379:134478.
11. Dai M, Yang F, Zhang Z, Liu G, Feng X. Energetic, economic and environmental (3E) multi-objective optimization of the back-end separation of ethylene plant based on adaptive surrogate model. J Clean Prod 2021;310:127426.
12. Guler OF, Sen O, Yilmaz C, Kanoglu M. Performance evaluation of a geothermal and solar-based multigeneration system and comparison with alternative case studies: energy, exergy, and exergoeconomic aspects. Renew Energy 2022;200:1517–32.
13. Chen Z, Zhou Q, Zhang Y, Zhang X. Energy, exergy and economic (3E) evaluations of a novel power generation system combining supercritical water gasification of coal with chemical heat recovery. Energy Convers Manag 2023;276:116531.
14. Rutala WA, Weber DJ. Guideline for disinfection and sterilization in healthcare facilities, 2008. US: Department of Health and Human Services: 2017.
15. Hong J, Zhan S, Yu Z, Hong J, Qi C. Life-cycle environmental and economic assessment of medical waste treatment. J Clean Prod 2018;174:65–73.
16. Dion M, Parker W. Steam sterilisation principles. Pharmaceut Eng 2013;33:6.
17. Cappia JM. Principles of steam-in-place. Pharmaceut Technol 2004;28:40–6.
18. Schieving A. Understanding USP <1231> water for pharmaceutical use [Online]; 2017. Available from: http://www.pharmtech.com/understanding-usp-water-pharmaceutical-use [Accessed 17 Oct 2022].
19. U.S. Pharmacopeia. <1231> Water for pharmaceutical purposes [Online]; 2019. Available from: http://www.uspbpep.com/usp29/v29240/usp29nf24s0_c1231.html [Accessed 17 Oct 2022].
20. McGain F, Moore G, Black J. Steam sterilisation's energy and water footprint. Aust Health Rev 2017;41:26–32.
21. International Standards Organisation. European standard ISO 17665-1: sterilization of health care products – moist heat – part 1: requirements for the development, validation and routine control of a sterilization process for medical devices. Geneva: ISO; 2006.
22. Davies FL, Underwood HM, Perkin AG, Burton H. Thermal death kinetics of Bacillus stearothermophilus spores at ultra high temperatures. Int J Food Sci Technol 1977;12:115–29.
23. Princeton University Environmental Health & Safety. Autoclaving procedure [Online]. Princeton University; 2019. Available from: https://ehs.princeton.edu/laboratory-research/biological-safety/autoclave-use/procedure [Accessed 17 Oct 2022].
24. Flowserve SIHI Pumps brochure. SIHI LEMD compact liquid ring vacuum pumps [Online]; 2019. Available from: https://www.sterlingsihi.com/cms/index.php?eID=tx_nawsecuredl&u=0&g=0&t=1665234713&hash=219c9ad670b4b3ea55a00f7b32a759625bf55193&file=fileadmin/Dokumente_WEB/Produkt_Kataloge/Vakuumpumpen/Fluessigkeitsring/Blockbauweise/englisch/TC_FLS_SIHI_LEMD_EN.pdf [Accessed 17 Oct 2022].
25. Vandoni G. The basis of vacuum [Online]. CERN; 2012. Available from: https://indico.cern.ch/event/264020/attachments/467855/648232/CERN-Basic-Vacuum-2012-lecture.pdf [Accessed 17 Oct 2022].
26. Idris A, Chu GK, Othman MR. Incorporating potential environmental impact from water for injection in environmental assessment of monoclonal antibody production. Chem Eng Res Des 2016;109:430–42.
27. The Engineering ToolBox. Metals and alloys – densities [Online]; 2019. Available from: https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html [Accessed 09 Aug 2019].

28. The Engineering ToolBox. Specific heat of common substances [Online]; 2019. Available from: https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html [Accessed 29 Jul 2019].
29. Eirgrid Group. System information – fuel mix [Online]; 2022. Available from: http://www.eirgridgroup.com/how-the-grid-works/system-information/ [Accessed 17 Oct 2022].
30. The Engineering ToolBox. Combustion of fuels – carbon dioxide emission [Online]; 2019. Available from: https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html [Accessed 06 Aug 2019].
31. The Engineering ToolBox. Combustion of fuels and nitrogen oxides (NOx) emission [Online]; 2019. Available from: https://www.engineeringtoolbox.com/nox-emission-combustion-fuels-d_1086.html [Accessed 06 Aug 2019].
32. Environmental Protection Agency. Natural gas combustion [Online]; n.d. Available from: https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf [Accessed 17 Oct 2022].
33. Rechenberger D. Natural gas is the most climate-friendly fossil fuel in electricity production [Online]. Available from: https://www.wingas.com/fileadmin/Wingas/WINGAS-Studien/Energieversorgung_und_Energiewende_en.pdf [Accessed 17 Oct 2022].
34. Environmental Protection Agency. Anthracite coal combustion [Online]; n.d. Available from: https://www3.epa.gov/ttn/chief/ap42/ch01/final/c01s02.pdf [Accessed 17 Oct 2022].
35. Chou CL. Sulfur in coals: a review of geochemistry and origins. Int J Coal Geol 2012;100:1–13.
36. Sustainable Energy Authority of Ireland. Conversion factors [Online]. Energy Statistics in Ireland; 2019. Available from: https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/ [Accessed 17 Oct 2022].
37. Electric Ireland. Electricity and gas price plans for new customers [Online]; 2019. Available from: https://www.electricireland.ie/switch/new-customer/price-plans/electricity-and-gas?priceType=D [Accessed 05 Feb 2019].